The railway connection

Frequency converters for railway power supply

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Electric railways have a huge demand for power. In fact many operate their own high-voltage power grids and some even own their own generating plants. Few railways, however, are totally autonomous: Power must be exchanged with the national grids. This is not as simple as it may at first seem. For historical reasons, many railway systems are electrified at frequencies other than those of the domestic grids, and furthermore, they are not always synchronized.

Historically, rotating machines were used to transform electricity from one frequency to another, with auxiliary equipment being added where needed to compensate for the frequency slip – within certain limits. The state-of-the-art solution is a different one however: New installations use large frequency converters based entirely on power electronics. These offer numerous advantages including faster response times and the ability to provide improved reactive power control.

Converters

Power electronics based frequency converters for the interconnection of unsynchronized grids or grids operated at different frequencies have been around for many years. These are mostly based on line-commutated thyristors. Only relatively recently, have converters with turn-off semiconductors been used for this purpose in the form of voltage source converters with DC link. The power supply of single-phase railway grids represents a special challenge. Only since voltage source converters have become available, have power-electronic systems been able to establish themselves in this area and replace the previously widely-used rotary frequency converters.

Historical review and current state

Today, three main different power systems are used for electric mainline railways.

In countries or regions where railway lines were electrified relatively recently (after the advent of power electronic devices allowing the speed of traction motors to be controlled), the catenaries are often fed from the public grid at a frequency of 50 Hz (or 60 Hz), mostly at a line voltage of 25 kV.

Before power electronic devices became available, other power supply systems had to be used. In some countries, where the railway lines were electrified much earlier, direct current (DC) was chosen (typical line voltages are 1.5 and 3 kV). The advantage of this system was the ease with which the speed of DC motors can be controlled. In other countries, alternating current was chosen and commutator motors were used. The speed of these motors can also be controlled easily, but as a frequency of 50 or 60 Hz was too high for the commutator, a lower supply frequency was adopted.

Railways operated with low-frequency single-phase alternating current can be found

- On the east coast of the USA: 25 Hz
- In Norway and Sweden: 16.7 ($16\frac{2}{3}$) Hz
- In Germany, Austria and Switzerland: 16.7 ($16\frac{2}{3}$) Hz

Frequency converters with a total power of nearly 1,000 MW have been taken into operation in the past 15 years. Approximately two thirds of these were supplied by ABB.

In the past, rotary converters consisting of two electrical machines with a different number of pole pairs arranged on a common mechanical shaft were used for the energy exchange between the railway and three-phase national grids. Two different designs exist: In the USA and Scandinavia, synchronous machines are used on both sides of the grid resulting in the grids being quasi "synchronized." The frequency ratio is fixed and cannot be changed. In central Europe, railway operators operated their own power stations using single-phase machines from the beginning and operated their own high-voltage transmission system independently of the three-phase national grid. The national and railway grids are thus not rigidly "synchronized", but the frequency ratio varies within limits. To accommodate this, the rotary converters had to be of a special design. These were so-called Scherbius machines. Synchronous machines were used only on the single-phase side. An induction machine with a wound rotor and slip rings was used on the three-phase grid. Additional (small) machine sets regulate the slip frequency in the rotor allowing speed variations (within a range).

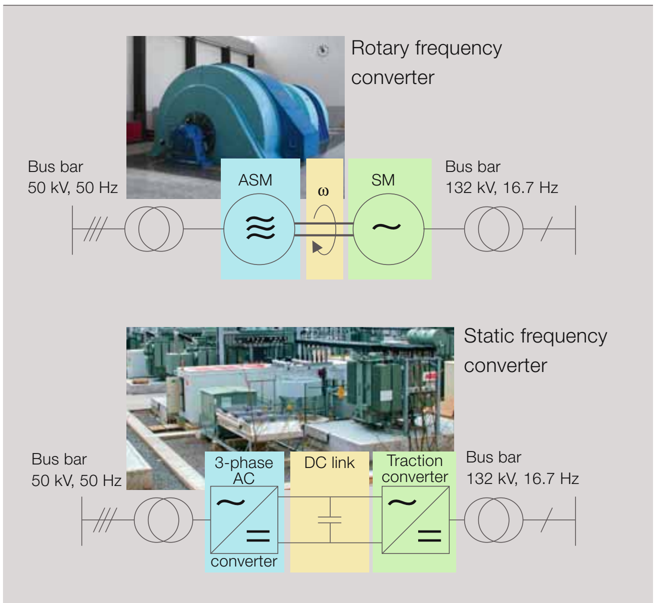
In a more recent development, power-electronic frequency converters in the form of voltage converters became suitable for this purpose. Hence rotary frequency converters are no longer produced. In fact, frequency converters with a total power of nearly 1,000 MW have been taken into operation in the past 15 years. Approximately two thirds of these were supplied by ABB. Another 600 MW of such converters are presently being built or have been ordered. Approximately 500 MW of these will be supplied by ABB.

Comparison with rotary converters

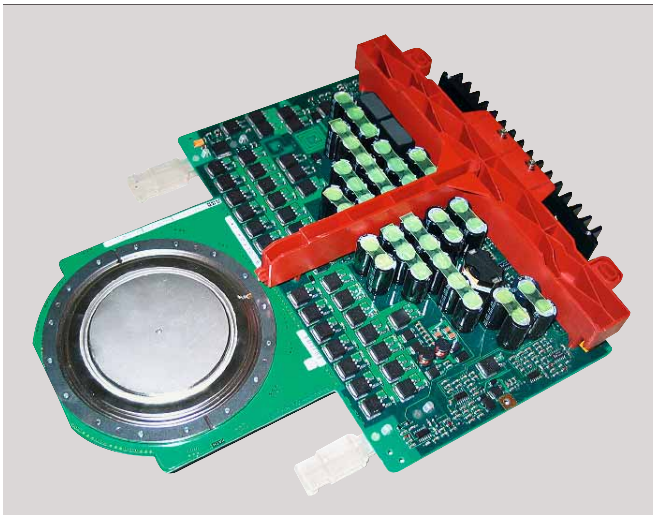
Conventional line-commutated converters have never been major contenders for the supply of such single-phase grids. In contrast to three-phase grids, switching patterns cannot be balanced. This results in unacceptable voltage distortions. Nevertheless, some direct converters (cyclo-converters) were built, but the harmonics affecting both grids are very large and cause disturbances in the operation of the grid. Another disadvantage of these converters lies in the fact that the power output fed into the single-phase grid fluctuates at twice the frequency of this grid. This fluctuation also manifests itself in and leads to disturbances of the three-phase grid.

It was only after the emergence of powerful turn-off semiconductors in the form of GTOs (gate turn-off thyristors), that self-commutated voltage source converters could be built.

1 A rotary frequency converter with an asynchronous machine (ASM) and a synchronous machine (SM) (top) and a static frequency converter for outdoor installation (below).



2 IGCT (integrated gate-commutated thyristor) with the semiconductor element in its presspack housing (left) and the gate unit (right). The gate unit is connected to the semiconductor by a multiple-layer printed circuit board with an extremely low inductance.



The interconnection of a three-phase and a single-phase grid places higher demands on both rotary converters and power-electronic converters than the interconnection of two three-phase grids. One principle reason for this is the fact that the power in the single-phase grid oscillates at twice the grid frequency. In the case of rotary converters, these torque and power fluctuations are absorbed and damped by the rotating masses. The resulting vibrations must however be absorbed by their mechanical anchoring and its foundations. This leads to additional complexity in the design of both the machine and its foundations.

Only after the emergence of powerful turn-off semiconductors in the form of GTOs (gate turn-off thyristors), could self-commutated voltage source converters be built.

Where voltage converters are used in this application, the oscillation is filtered using a capacitor bank and an inductance, tuned to double the operating frequency of the single-phase grid.

Another challenge lies in the fact that such a system does not only have to act as a voltage and reactive power source, but must also be able to handle – without interruption – the transition from interconnected system operation to island operation in case of disturbances in the grid. Furthermore, it must be capable of acting as the sole power supply to one isolated section of railway, and be able to re-synchronize with the rest of the railway-side grid after a disturbance has been cleared 1.

Examples of frequency converters

Static converter technology has a long tradition at ABB. The first railway power supply converters were taken into operation in Sweden. However, the technology deployed was not very suitable for use in central Europe where the structure of the railway power grid was considerably different and the requirements on the voltage quality higher. The first two modern frequency converters, rated at 25 MVA each, were put into operation in 1994 in Giubiasco (Switzerland). Following the success of this project, GTO technology was developed further, and in 1996 a 100 MVA converter went into service in Bremen (Germany). This converter was equipped with "hard-driven" GTOs. These were GTOs with a concentric gate and a gate unit feeding the control signal to the gate via an extremely low-inductance lead. The result was a substantially improved switching performance for the semiconductors. This technology was eventually applied to a railway converter station in Karlsfeld (Germany) with a rating of 2 × 50 MW/67 MVA put into service in 1999.

The next step was the development of a new semiconductor element, the integrated gate-commutated thyristor (IGCT).[1] This was a development of the GTO and featured much better switching capabilities, lower losses, and the low-inductance gate unit as an integrated "component." The compact design finally led to the development of standardized converter modules and permitted converters of different power classes to be built. Today, 21 converters in the 15 to 20 MW range are in operation and performing to the customers' fullest satisfaction. Due to the modular design, other power classes can be implemented very easily, most appropriately in steps of 15 MW. These are achieved by connecting the converter modules and the converters based on them in parallel.

This converter generation sets new standards in terms of performance, footprint and short erection/commissioning times. The positive feedback

Footnote

1) For more background on IGCTs, see "A tiny dot can change the world" on pages 15–18 of this edition of *ABB Review*.

Converters

from customers shows that the standardized railway converter from ABB is well suited to cover their needs.

The base module

The "heart" of the converter module, the IGCT, is shown in 2. The IGCT combines the advantages of the GTO and the IGBT (insulated-gate bipolar transistor), ie, robustness, low switching and conduction losses as well as a fast switching capability. The properties of this semiconductor element remain unsurpassed for the application discussed here (high power, medium voltage). An IGBT for the same application (high-voltage IGBT, IEGT), for example, exhibits comparable switching losses in relation to the same silicon surface, but considerably higher conduction losses. Furthermore, the IGCT allows a converter design with minimal additional circuitry. For example, a phase module only requires a simple snubber circuit whereas each GTO requires extensive circuitry. This results in advantages in terms of costs, compactness and losses.

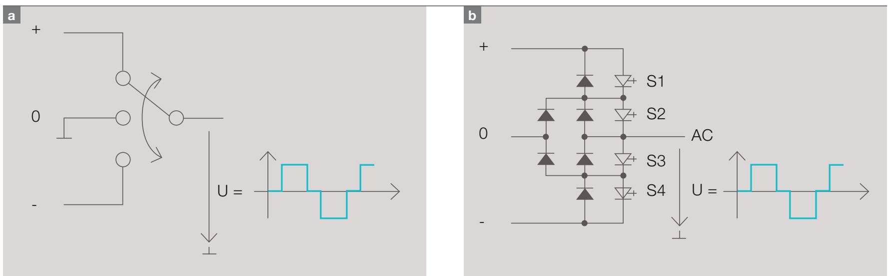
Losses occur whenever a semiconductor conducts current or is switched. Such losses can be minimized by lowering the switching frequency. On the other hand, the switching frequency should not be too low because of the harmonics generated. Hence, there is an optimization potential between losses and harmonics. An elegant way to partially overcome this dilemma is to choose a multi-level topology. This allows the converter to be operated with a relatively low switching frequency and at the same time achieve good harmonic performance.

The IGCT combines the advantages of the GTO and the IGBT, ie, robustness, low switching and conduction losses as well as a fast switching capability.

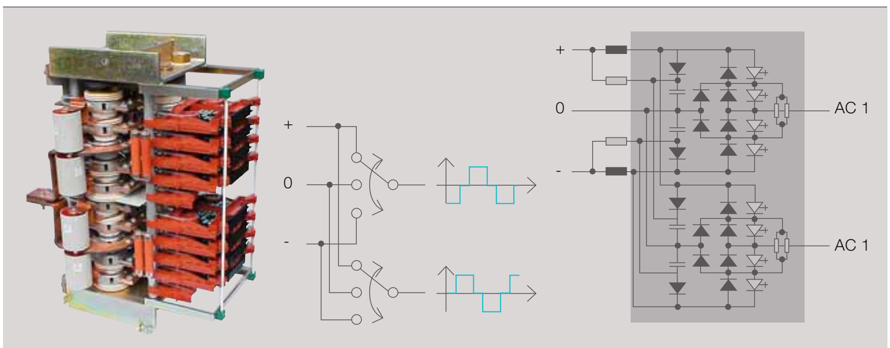
Three-level phase modules are used to generate an AC voltage from a DC voltage. Such modules can be considered as changeover switches with three positions: The output can be switched to the positive (+), neutral (0) or negative potential (-) of the DC link 3.

Two-phase modules of this type are combined to a three-level double-phase module. All IGCTs are cooled on both sides. The cooling medium (a water-glycol mixture) is fed via hose connections to the heat sinks. The mechanical structure of the double stack allows a very compact design. This helps achieve the required low stray inductance values within the stack allowing the semiconductors to be utilized to the optimum. Nevertheless, access to all semiconductors in the stack is still possible permitting easy replacement. Each semiconductor can be replaced with the help of a simple tool without interrupting the cooling circuit. 4 shows an example of such a double stack.

3 Operating principle of the three-level converter module and its implementation with semiconductor devices



4 Mechanical structure of a double stack and the corresponding circuit diagram



Example: 15–20 MW class converter

5 shows the schematic of a complete converter station.

50 Hz converter (SR50)

The 50 Hz converter 5a has the following attributes:

- *Design:* The 50 Hz converter consists of two standard three-phase, three-level units. Two phases are combined in one stack to form a double-phase module. A double-phase module of a three-level unit consists of eight IGCTs combined with eight freewheeling diodes, and four freewheeling diodes on the neutral conductor. The gate unit and the GCT form an integrated unit, the IGCT. The clamping circuit serves as a di/dt limiter and voltage limiter. It consists of current-limiting reactors, capacitors and clamp diodes with resistors.
- *Circuitry and control method:* The 50 Hz converter is built in real 12-pulse configuration. Hence, only 12-pulse characteristic harmonics ($n = 12k \pm 1$; $k = 1, 2, 3, 4 \ldots$) are generated. Depending on the chosen semiconductor switching frequency and the modulation strategy, some of the remaining harmonics can be cancelled. If needed, the harmonics can be damped to even lower values by applying a line filter.

16.7 Hz converter

The 16.7 Hz converter 5b has the following attributes:

- *Design:* The 16.7 Hz converter consists of four standard two-phase, three-level units. Two phases are combined in one stack assembly to form a double-phase module, which

can be used to form a single-phase H-bridge. A double-phase module consists of the same elements as described above for the 50 Hz converter.

- *Circuitry and control method:* The 16.7 Hz converter is implemented in an eight-step configuration. The converter output voltage levels are summed up by means of series connection of the line side transformer windings of the four offset-pulsed three-level H-bridges. The individual H-bridges are operated in three-pulse mode using a conventional PWM (pulse-width modulation) technique.

A multi-level topology allows the converter to be operated with a relatively low switching frequency and at the same time achieve good harmonic performance.

Voltage limiter

Should the DC link voltage exceed an upper threshold, it is discharged via a resistor until a lower threshold is reached 5c. The voltage limiter control works independently of the control system for the converter on the two-phase AC (railway-side) and the three-phase AC (mains-side). This ensures that the DC link voltage remains within the defined range at all times.

DC link

All double-phase modules of the converter are connected to each other on the DC side by a common bus bar carrying the connections for the individual converter modules – for the directly coupled DC link capacitors as well as for the DC link filter banks and for voltage measurements.

The DC link forms the connection between the 50 Hz and 16.7 Hz converters. The DC link consists of the following main components:

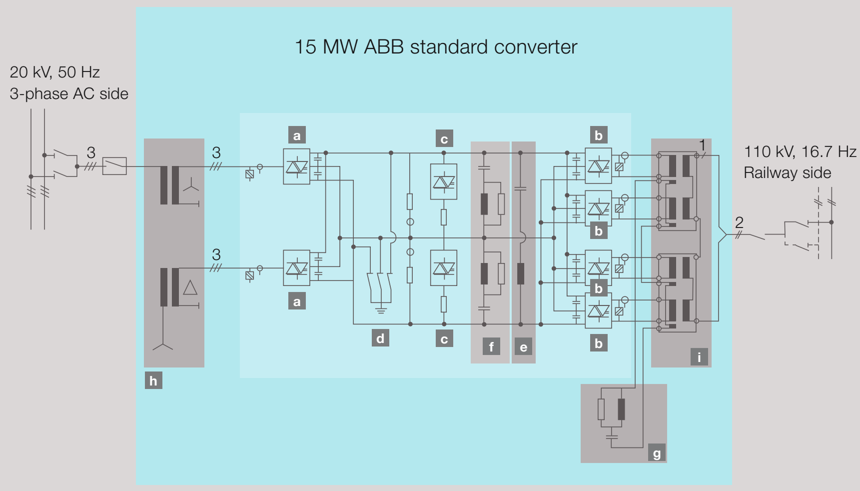
- Directly coupled capacitor bank used as energy storage
- 33.4 Hz filter to absorb the power fluctuation from the railway grid 5e
- High-pass filter to absorb the higher frequency harmonics from the railway grid, in particular the distinct third and fifth harmonics of the railway grid 5f

Both DC link filters – together with the directly-coupled capacitors – also serve as energy storage. This is required for control reasons. The capacity of the energy storage is sufficient to face an unexpected load shedding of P = 100 percent fast enough to keep the DC-link voltage within specified limits.

33.4 Hz filter

The purpose of the 33.4 Hz notch filter is to absorb the power pulsations from the railway grid 5e. Despite the high quality factor of approximately

5 Schematic diagram of a converter station



Other variants:
110 kV, 50 Hz 3-phase AC side
15 kV, 16.7 Hz railway side

- a 2 x 3-phase 3-level bridges
- b 4 x 1-phase 3-level bridges
- c Voltage limiter
- d Grounding, measurement
- e 33 Hz filter
- f high-pass filter
- g 16.7 Hz filter
- h 50 Hz transformer
- i 16.7 Hz transformer

Converters

200 (ie, low damping), the filter exhibits a relatively broad-banded characteristic around its center frequency due to its high capacitive performance. This allows specified railway frequency deviations to be absorbed. In addition, filter losses are relatively low as the capacitors generally exhibit significantly lower losses than the reactors.

High-pass filter

The high-pass filter absorbs the lower-frequency harmonics originating mainly from the railway grid 5f. The filter is set up as damped second-order absorption circuit tuned below the fifth harmonic of the fundamental frequency of the railway grid. This is due to the distinctive third and fifth harmonics of the railway grid voltage which are reflected as second, fourth and sixth in the DC link. The higher-frequency harmonics from the three-phase grid and the railway grid as well as those caused by the pulsing are partially absorbed by this filter as well but mainly by the directly coupled capacitors of the converter. Hence, the expected harmonics in these grids are also being taken into account in the dimensioning of these components.

Converter container

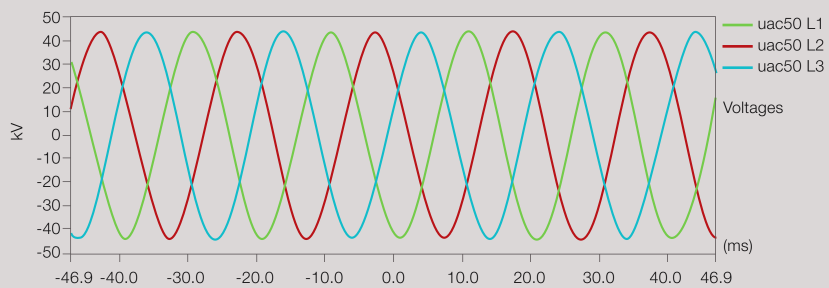
The converter and the associated control system come fully wired and tested in a weatherproof container. The cooling system is supplied in a separate container. Both containers are mounted onto a common support base. 6 shows a cross-sectional view of the converter container.

Compared with the typical frequency spectrum of machines, the frequency spectrum of the output voltage formed by the individual levels exhibits only very low harmonics in the low frequency range.

Converter transformers

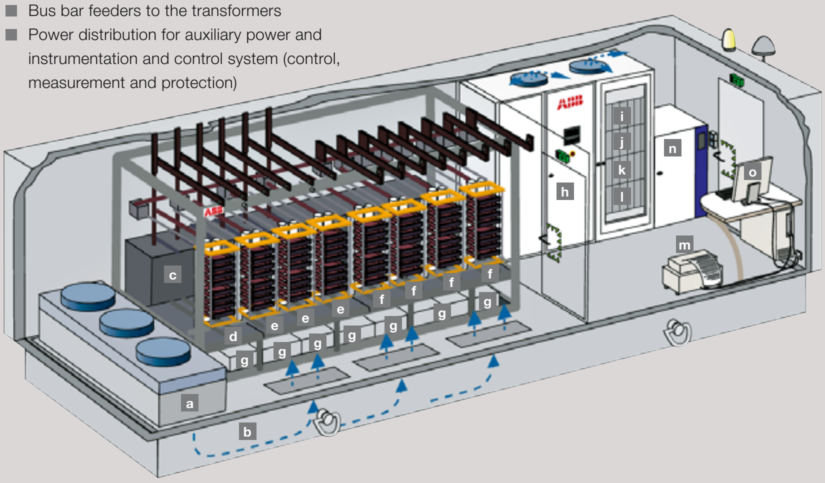
- *50 Hz transformer:* The 50 Hz transformer of the 50 Hz converter feeds the two IGCT-based three-phase

7 The three-phase voltages on the connection point of the 50 Hz grid



6 Converter container

Converter container including:
- Space cooling system
- Converter and voltage limiter modules with control electronics close to the converter
- DC-link bus bars and capacitors behind the converter modules
- Bus bar feeders to the transformers
- Power distribution for auxiliary power and instrumentation and control system (control, measurement and protection)
- Uninterruptible power supply for the instrumentation and control system
- Local operation via HMI and event printer



a Space cooler
b Cooling air
c C bank / DC bus bar
d Voltage limiter
e 50 Hz converter
f 16.7 Hz converter
g Valve-based electronics
h Auxiliary power
i Open-loop control
j Closed-loop control
k Measurement
l Protection
m Event printer
n UPS
o HMI (Human Machine Interface)

Factbox Advantages of static (power electronic) frequency converters in comparison with rotary converters

Costs
Taking into account the overall costs including auxiliary systems, construction and assembly, the capital costs and running costs for static converters are considerably lower.

Efficiency
Static converters offer an efficiency of approximately 97 percent (including transformers connecting to both grids) over a wide operating range. The efficiency of rotary converters varies from below 90 to 95 percent depending on the size and operating point.

Availability
Due to longer maintenance downtimes and repair times, the availability of rotary converters is considerably lower.

Operational behavior
Due to the absence of rotating masses in static converters, the response times are considerably shorter. Potential stability problems in case of grid disturbances due to rotor oscillations do not exist.

bridges. A three-phase transformer consists either of a three-limb core in double-tier design with intermediate yoke or of two three-limb cores contained in one tank. Each (part-) limb carries a high-voltage winding and a valve-side winding. The two high-voltage part-windings are connected in series. The high-voltage winding is Y-connected. The two valve-side windings are electrically offset by 30° (Y/D connection) to allow a 12-pulse operation of the converters.
The resulting connection is:
YN y0 d11

- *16.7Hz transformer:* The 16.7 Hz transformer of the 16.7 Hz converter serves to add up the four partial voltages to a nearly sinusoidal single-phase voltage with a rated frequency of 16.7 Hz. The transformer consists of four single-phase units. The rectangular partial voltages are generated from a DC voltage source (DC link) with the help of four single-phase IGCT converter bridges using the pulse width modulation method and fed to the four valve-side windings of the transformer. The adding-up and adaptation to the railway grid voltage is done in the high-voltage winding. A filter is connected to the series-connected tertiary windings or to the railway grid.

Line filter

On the 16.7 Hz side, a filter is used to reduce the very low harmonic distortion caused by the converter to even lower values. On the 50 Hz side, this is required in some cases as well.

The output voltages of the IGCT converters form rectangular pulses with a controllable width. Compared with the typical frequency spectrum of machines, the frequency spectrum of the output voltage formed by the individual levels exhibits only very low harmonics in the low frequency range. With regard to the grid, the converter represents a harmonic voltage source. The inductance of the transformer has a damping effect that is particularly marked for the higher current harmonics. This in turn positively affects the quality of the grid voltage. To further enhance the effect of the transformer inductance, a filter is provided, which further reduces the harmonic voltages. The resulting harmonic distortions remain below the required values. 7 illustrates the good quality of the voltage on the grid connection point of a converter (oscillogram recorded during commissioning).

8 shows a converter group in a substation with four converters of the 15–20 MW class.

Outlook

ABB's relatively large market share for this type of system shows that the targeted development of the converter technology was in accordance with the customers' requirements. In addition, the modular approach allows a flexible response to various performance requirements. Converter units rated at 30 MW and higher are currently under construction, and huge efforts are being made by ABB to remain successful on the market with this highly demanding technology.

8 15-20 MW class frequency converter station for the power exchange between the 50 Hz national grid and the single-phase 16.7 Hz railway grid. On the left the 50 Hz transformer with three-phase AC filters mounted on the gantry above, in the middle the converter container, and on the right the single-phase low-frequency transformer.

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